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SCATTERING COMPUTATIONS AS A SIMULATION TOOL FOR AUTOMATIC TARGET RECOGNITION AND PROCESSING

Yale University Computational Mathematics program

R. Coifman and V. Rokhlin

This research aims at improving most steps involved in the ATD/R process. This program is integrating the signal processing approach with analytic numerical analysis (used as a tool for the modeling of physical phenomena) to obtain clear and efficient definitions of target and clutter features.

The goal of the project is to enhance all aspects of processing, modeling and simulation of target recognition and detection. Our effort can be roughly subdivided into two parts: signal processing techniques, and methods for the numerical simulation of scattering phenomena. Following is a discussion of our work in these two directions of research.

I. Signal Processing Techniques.

We have developed over the last few years an integrated set of methods centered around the design of problem-specific waveforms. This Adapted Waveform Analysis toolkit is ameliorating the processing steps involved in ATR, either by accelerating the computation or by providing new means of analysis and modeling, as well as for extracting features to improve classification.

Adapted waveform analysis extends Fourier analysis to a broader collection of waveforms (with better time frequency localisations), where the choice of waveforms for analysis is made to accelerate computation or to provide a good fit between the class of targets and the corresponding waveforms (enhancing ATR).

These methods have already been successfully tested on Radar data, as well as other classes of sensors (acoustic, magnetic resonance, mechanical vibration, etc). The waveform used in adapted waveform analysis consist (in the high frequency case) of various libraries of orthonormal bases of localized trigonometric polynomials, or specific exponential sums (as arising in the Fast multipole method for Helmholtz equations). And in the low frequency

case of libraries and wavelets and wavelet-packets, again corresponding to multipoles for the Laplace equation.

Accomplishments:

We have continued the development of a toolkit for AUTOMATIC diagnostic feature extraction, in which the features selected for classification are optimised for optimal separation and parameter estimation. These methods have been applied and validated on radar returns from Lockheed Martin, as well as on a variety of other sensor data and are currently being prepared for insertion.

Our algorithms for fast computation of electromagnetic scattering have been substantially enhanced and are incorporated into engineering code at Hughes Research Lab and Boeing Corp. In particular a perturbative approach has been developed to permit modeling of the effect of rough subwavelength features; this approach has been extensively tested for perturbations off a flat plane and analysed for extension to general surfaces. It promises in combination with the FMM method to permit efficient realistic target simulation.

Moreover the detailed analysis of the effect of higher-order approximations can provide better image reconstruction algorithms suppressing speckle.

We have developed a variety of new libraries of waveforms including brushlets extending Radon transforms. These can be optimised to various processing needs including:

- Time and frequency domain scattering computations
- Image and video compression
- Image analysis, denoising segmentation and ATR
- Diagnostics and classification of sensor data
- New waveforms for spread spectrum communication with apparent random structures have been discovered and are being combined with phase randomization procedures introduced by Auslander/Barbano (to be tested by Hughes SpaceCom).

All of these are currently being tested and converted to DOD applications through various projects.

II. Numerical Simulation of Scattering Phenomena

During the last year, we undertook the following lines of research.

1. Improved versions of the FMM. Over the last few years, it has become increasingly clear that the Fast Multipole Method (FMM) and related techniques can bring many of the problems faced in computational electromagnetics within practical reach. As a result, we are spending a significant portion of our time on improving the performance of FMM implementations (rather than exploring *new* techniques with radically improved asymptotic CPU time estimates for other applications); following is a brief description of our FMM-related work.

When the surfaces involved in an electromagnetic simulation are rough on the scale of the wavelength, existing high-frequency FMM implementations begin to lose efficiency. We have therefore been developing a subwavelength or low-frequency FMM (LF-FMM) which remains efficient all the way to zero frequency (where the governing equation becomes the Laplace equation). We began, two years ago, by constructing a new version of the FMM for the Laplace equation, which replaces the classical multipole expansion with a representation in terms of *evanescent* plane waves, in order to diagonalize certain translation operators. That scheme bears some resemblance to the high-frequency FMM which achieves its numerical efficiency by representing the scattered field in terms of propagating plane waves. In our new LF-FMM, we use a combination of evanescent and propagating modes which blend the zero frequency and high-frequency FMMs together seamlessly.

The starting poin for our analysis is the integral representation

$$\frac{e^{i\omega r}}{r} = \frac{1}{2\pi}\int_0^\infty e^{-\sqrt{\lambda^2-\omega^2}z}\int_0^{2\pi} e^{i\lambda(x\cos\alpha+y\sin\alpha)}\frac{\lambda}{\sqrt{\lambda^2-\omega^2}}d\alpha d\lambda. \qquad (1)$$

Note that, for $0 \le \lambda \le \omega$, the modes propagate without attenuation, while for $\omega \le \lambda \le \infty$, they decay. The first region is referred to as the "propagating" part of the spectrum and the second as the "evanescent" part. After discretization, one has a representation of the field in terms of plane waves, for which translation from a source box within the FMM to a target box is particularly efficient. A report describing the mathematical theory underlying the new scheme is enclosed.

During the past year, the non-adaptive version of the FMM for the Laplace algorithm has been published, and we have completed work on the adaptive

version as well. The adaptive scheme has a break-even point when compared with direct calculation at about 1,200 nodes in single precision, more or less independent of the manner in which the nodes are distributed. For three-digit precision, the break-even point is about 400 nodes; for 10 digits, it is about 4,000 nodes. A paper describing the full algorithm is near completion. Implementation work is currently underway for the LF-FMM, and we expect the break-even points to be comparable to those cited above for the Laplace FMM.

2. Non-Reflecting Boundary Conditions For the Wave Equation.

A longstanding practical issue in numerical wave propagation and scattering problems concerns the reduction of an unbounded domain to a bounded domain by the imposition of nonreflecting boundary conditions at an artificial boundary. In "time-domain" calculations, it is well-known that the exact nonreflecting conditions are global in both space and time. While the problem has been widely studied (see Givoli [1] for an overview), the boundary conditions used in practice typically introduce serious numerical artifacts. The two most common approaches are based on the construction of local differential boundary conditions [2, 3] or absorbing regions [4, 5], but neither provides a clear sequence of approximations which converge to the exact, nonlocal conditions. Recently, Sofronov [6] and, independently, Grote and Keller [7] have developed and implemented an integrodifferential approach for three-dimensional calculations using a spherical boundary and have demonstrated that high accuracy can be achieved at reasonable cost. In their schemes, the work is of the same order as the explicit finite difference or finite element calculation in the interior of the domain. For N^2 points on the spherical boundary, $O(N^3)$ work is required. Hagstrom and Hariharan [8] have shown that these conditions can be effectively implemented using only local operators, but at the cost of introducing a large number of auxiliary functions at the boundary. A somewhat more general, but closely related, integral formulation is introduced in [9, 10]. The fundamental analytical tool in the latter papers is what we refer to as the "nonreflecting boundary kernel" which is the inverse Laplace transform of the logarithmic derivative of a Hankel function.

We have now shown that the logarithmic derivative of a Hankel function can be approximated as a ratio of polynomials of modest degree, so that its inverse Laplace transform can be expressed as a sum of exponentials. Using this approach, the cost of computing the nonreflecting boundary condition is comparable to that of a fast Fourier or spherical harmonic transform.

For two-dimensional problems, $O(N \log N \log \frac{1}{\epsilon})$ work is required at each time step, where N is the number of points used in the discretization of a cylindrical (circular) boundary. In three dimensions, the cost is proportional to $N^2 \log^2 N + N^2 \log N \log \frac{1}{\epsilon}$, for a spherical boundary with N^2 points. The first term comes from the calculation of the spherical harmonic transform using the fast algorithm of [11, 12]. This cost is negligible compared with the work associated with the finite difference or finite element calculation being carried out over the enclosed volume.

A report describing this work is enclosed.

3. Prolate Spheroidal Wave Functions, Quadratures, and Interpolation

Whenever band-limited signals are measured or generated, the locations of receivers or transducers have to be selected; it is well-known that different distributions lead to very different resolutions given a fixed number of receivers or transducers. A closely related set of issues is encountered in the numerical solution of scattering problems: given a scatterer, one would like to find nodes on its surface leading to most efficient discretizations.

During the last year or so, we discovered (somewhat serendipitously) that whenever band-limited signals are to be discretized, measured, or generated, the construction of optimal (in a very strong sense) configurations of nodes is a tractable problem. When the nodes are to be located on a line or on a disk in R^2, the solution is a fairly straightforward consequence of classical results obtained by Slepian and his collaborators more than 30 years ago. We have constructed the necessary numerical tools, which are quite efficient; the resulting discretizations are a dramatic improvement over the ones currently employed.

Construction of optimal configurations of nodes on more complicated regions requires additional mathematical apparatus; such apparatus has been largely (but by no means completely) designed. Unfortunately, the numerical tools we have constructed are quite inefficient in this environment, which limits the size of regions on which we are currently able to design optimal configurations by approximately three wavelength. Needless to say that this state of affairs is not satisfactory; we are currently working on improved (in terms of CPU time requirements) algorithms for the construction of such configurations.

At the present time, we are finalizing the first of a series of papers describing this work (this paper describes the one-dimensional version of the

theory).

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